

TRADEOFFS IN CEREAL RYE MANAGEMENT STRATEGIES PRIOR TO
ORGANIC SOYBEAN

A Thesis

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ABSTRACT

Cover crops can cycle nutrients, enhance soil health, and suppress weeds, thereby reducing the need for inputs and decreasing environmental problems associated with nutrient losses, soil erosion, and non-target herbicide effects. In organic crop production, cover crops are often essential for optimizing cropping system performance. This research aimed to compare three cereal rye (*Secale cereale*, L.) management strategies for their agronomic, soil health, and economic benefits in organic soybean (*Glycine max*, L.) production. In 2014-2015 and again in 2015-2016 in central New York, we compared 1) a 'No cover' treatment, in which no cover crop was seeded and the soil was moldboard plowed prior to planting soybeans, 2) a 'Plow down' treatment, in which cereal rye was terminated with a moldboard plow at jointing stage prior to planting soybeans, 3) a 'Ryelage' treatment, in which cereal rye was harvested at boot stage for forage, followed by moldboard plowing prior to planting soybeans, and 4) a 'Roll down' treatment, in which cereal rye was roller-crimped, followed by no-till planting soybeans.

Soil health analyses showed greater water infiltration and higher soil respiration in the 'Roll down' treatment compared to the 'No cover' treatment, and greater potentially mineralizable nitrogen (PMN) in the 'Plow down' treatment compared to the 'No cover' and 'Ryelage' treatments in 2016. No significant differences were observed in aggregate stability or active carbon. Weed biomass in soybean was greater in the 'Roll down' treatment than in the other three treatments in both years. No significant differences were observed in yield in 2015, but in 2016,

yields were lower in the 'Roll down' treatment, which was probably due to a combination of extremely dry conditions in June, poor seed-to-soil contact, and reduced soybean growth rate. Economic analysis showed that harvesting cereal rye for ryelage and using tillage prior to growing organic soybean can maximize profitability. Overall, this research shows that cover crops can provide many benefits; however, no one cover crop management strategy provided all benefits and more research is needed to overcome tradeoffs.

BIOGRAPHICAL SKETCH

Kiera Crowley was born in Washington State, but since the age of 11 her home has been in Ithaca, NY. Before coming to Cornell, she pursued a dual degree in geography and Chinese at Colgate University, and conducted research on ecological agriculture in China on a Fulbright Scholarship.

Kiera's interest in agriculture was first sparked by a seminar class she took in freshman year of college called Human Impact on the Environment. In that class, she read Michael Pollan's *Omnivore's Dilemma* and Bill McKibben's *Deep Economy* – books that discuss the environmental problems caused by industrialized agriculture and the possibility for a more sustainable approach. She was appalled to learn about the many aspects of industrialized agriculture that threaten the environment: the fuel-intensive machinery and production of agricultural chemicals that contribute to global warming and rely on the destructive extraction of finite resources; the pollution of soil and waterways caused by the use of those chemicals; the inefficient and unsustainable use of water resources; and the soil erosion and degradation that results from excessive tillage and monocultures. She was especially horrified to learn from watching *Dirt! The Movie* that one third of the world's topsoil – the most biologically active and agriculturally important layer of soil – has been lost, posing a severe threat to our ability to keep producing enough food for future generations. Upon learning about these problems, she decided she wanted to become part of a movement to create a more sustainable food system – one that does not degrade the environment on which it depends, and one that provides plenty of nutritious food for generations to come.

Through coursework at Colgate, Kiera became particularly interested in agriculture in developing countries, where agriculture is not yet heavily industrialized, thereby presenting an opportunity to develop a more sustainable approach. With this in

mind, she applied for a Fulbright Scholarship, which she used to research the development of sustainable agriculture in China via farm visits and extensive interviews. Her research there focused on farms claiming to employ “ecological” methods, and she found that they had a common theme: many of the farm founders have little to no experience or knowledge of effective ecological methods. This was leading to large crop losses from weeds, pests, and disease, and ultimately the general conception that ecological, or organic agriculture will never be a high-yielding or financially sustainable industry. She found herself getting into discussions about what practices were or were not sustainable, and wishing that she had more answers. At one point, she wrote down a list of questions that had been piling up in her head: *“How does farming with chemical fertilizer and pesticides impact soil health?”*; *“What organic methods are most effective at rebuilding soil health?”*; *“How do you assess soil health?”*; *“Is there a way to control weeds on small-scale farms that is less labor-intensive?”* She decided that in order to play a role in making agriculture more sustainable, she needed to be able to answer these and other questions about the science behind sustainable agriculture. She started to consider pursuing a degree in sustainable agriculture to start working towards those answers.

Kiera’s desire to pursue a degree in sustainable agriculture solidified when she attended an international conference in Ningxia Province titled “Water Conservation and Ecological Restoration.” There, she heard Ray Weil give a talk on roller-crimping cover crops for weed and soil management. She was intrigued by the idea that this roller-crimper, which terminates cover crops by rolling and crimping them, could make it possible for organic agriculture to be no-till, and still effectively control weeds. She went to talk to Ray after his talk, and ended up traveling around with him to garden plots and farms in the area. He was looking at soils, talking to farmers about

management practices, and giving them advice, and she was translating for him and learning alongside him. She thought, “I want to be able to do that!”

In the process of looking for a graduate program and a professor with whom to carry out her degree, Kiera found that much of the current research in sustainable agriculture was focused on cover crops. The more she learned about cover cropping, the more interested she became. Although most of the research on cover crops was being done in the context of industrialized agriculture and not in the context of the small-scale, local agriculture that she had become passionate about in college, she was excited by the practical potential of cover crops to provide a sustainable approach to managing soils and weeds on a large scale. As she thought about it, she began to realize that since a restructuring of the agricultural system in this country would not happen overnight, it is important to work on improving the systems that take up the majority of our agricultural land, which happen to be corn and soybean production. In addition, she realized that the knowledge she could gain from studying cover crops would be applicable to many systems, including small-scale ones. Thus, Kiera came to Cornell excited to learn the intricacies of cover crop management and how it could be optimized to improve the sustainability of agricultural systems.

I would like to dedicate this manuscript to Tim Phelps, for all his love and support throughout the project and writing process.

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I owe a big thank you to Chris Pelzer, our lab manager, for conducting many of the field operations in this experiment, for helping me plan sampling and organize field work, and for always being there, graciously answering my many questions throughout the field season and writing process. I also owe a big thank you to Sandra Wayman, our lab technician, for helping plan, organize, and conduct fieldwork, for always being enthusiastic and ready to work hard, and for providing valuable input to help me improve my various presentations.

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Finally, I would like to thank my mom and dad, and Tim Phelps, for their unwavering support and encouragement throughout these last two years.

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INTRODUCTION

It is widely recognized that organic agriculture has some environmental benefits over conventional agriculture. Compared to conventional systems, organic cropping systems generally exhibit lower N₂O and total greenhouse gas (GHG) emissions, greater plant and faunal diversity, higher soil organic carbon content, enhanced soil structure and water-holding capacity, reduced soil erosion, reduced pesticide and nitrate leaching, and increased profitability (Seufert and Ramankutty, 2017; Reganold and Wachter, 2016). However, organic agriculture still represents a relatively small portion of agriculture in the US today – about 0.7 percent of all US farms as of 2012 (National Sustainable Agriculture Coalition, 2014). Barriers to adoption of organic crop production include increased weed problems, nutrient supply challenges, increased labor, lower yields, and reduced profitability during the three-year transition period, due to a lack of premium prices.

Many of the barriers to adoption of organic production stem from weeds. Weed management in organic systems is labor-intensive, and weeds often contribute to lower yields. Traditionally, organic agriculture has relied on soil tillage and cultivation for weed control. However, tillage is fuel- and labor-intensive, and excessive tillage leads to destruction of soil structure and compaction. No-till has been promoted as an alternative that reduces fuel and labor expenses associated with tillage, preserves soil structure, reduces compaction, and improves overall soil health. However, no-till management, especially continuous no-till, can be challenging in organic systems where synthetic herbicides are prohibited.

Soil health has been defined as “the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans,” (USDA-NRCS, 2012), and is important to consider when making management decisions for any

production system, organic or conventional. A healthy soil has plenty of organic matter, good tilth, sufficient nutrient supply, good drainage, resistance to erosion, and high populations of beneficial microorganisms (Magdoff, 2001). In the past, soil chemical and physical properties have dominated the dialogue around soil health (or soil quality), but increasingly, the critical role of soil biology is being recognized (Lehman et al., 2015). All three components are essential to the functioning of the soil ecosystem. The chemical health of the soil is determined by the availability of micro- and macronutrients, the pH, cation exchange capacity, and salinity/sodicity of the soil, and the presence of heavy metals (Moebius-Clune et al., 2016). Physical soil health is based on soil structure, which determines how much water can infiltrate, how much moisture is retained, the amount of microbial activity, and the stability of soil aggregates. Soil biological health involves the activity of soil biota, which play key roles in nutrient cycling, preservation of soil structure and fertility, control of erosion, mitigation of floods and droughts, and control of pests and pathogens, among other functions (Lehman et al., 2015).

Cover crops offer a solution both for managing weeds and improving soil health in organic production. Cover crops seeded in the fall can out-compete weeds both in the fall and in the spring before planting, and have the potential to decrease weed-crop competition by reducing weed abundance and seed rain, producing phytotoxic chemicals, immobilizing nutrients, producing smothering residues, and changing soil structure and quality (Hodgdon et al., 2016). Cover crop benefits to soil health include reducing erosion, runoff, and nitrate leaching, increasing soil water infiltration and storage, enhancing microbial populations and habitat for beneficial insects, and reducing root disease and plant-parasitic nematodes (Kaspar et al., 2001; Magdoff, 2001; Reicosky and Forcella, 1998). Cover crops can also sequester carbon in soils (Kong et al., 2005; Kuo et al., 1997; Poeplau and Don, 2015). For example,

McDaniel et al. (2014) conducted a meta-analysis on the effects of cover crops using over 122 studies and found that crop rotations that include cover crops had 8.5% more total carbon than those without cover crops.

Cereal rye (*Secale cereale*, L.) has been shown to be an ideal cover crop because it can be planted later in the fall than other cover crops, reduces soil erosion, scavenges nitrogen, produces a large amount of biomass, and is highly weed-suppressive. Cereal rye, originally brought to the northeastern United States by English and Dutch settlers, is a cool season, annual grass that can grow 0.9 to 1.8 m tall (Casey, 2012). It has flat leaf blades and an awned, spike-like inflorescence. Cereal rye has been shown to improve soil biological and physical health. It can increase soil organic matter (Villamil, 2006; Lal et al., 1979), particulate organic matter (Surapur, 2014), total organic carbon (Liu et al., 2005), soil microbial biomass (Mendes et al., 1999), soil aggregation (Liu et al., 2005; Sainju et al., 2003), and aggregate stability (Steele et al., 2012). By reducing plant-available nitrogen, cereal rye can be used to suppress weeds, which is particularly relevant in legume crops that fix their own nitrogen and grow well in low soil nitrogen conditions (Wells et al., 2013).

In addition to its use as a cover crop, cereal rye can be harvested for grain for foods, alcoholic beverages, livestock feed, and seed, included in pastureland, or cut for hay (Casey, 2012). Interest among dairy farmers in using winter cereals as a double crop has increased in recent years in the northeastern United States due to extreme weather in 2012 and 2013 that impacted corn silage and hay yields (Ketterings et al., 2015). In addition, interest among organic dairy farmers has increased due to the expense of organic feed (Jemison et al., 2012). Although double cropping with small grains such as cereal rye and soybean is common in the southern United States, the shorter growing season in New York State prevents farmers from harvesting grain

from cereal rye and then planting soybean. However, cereal rye can be harvested as haylage, or ‘ryelage’, months before grain, allowing farmers in New York State to plant full season soybeans.

Cereal rye in conventional systems is typically killed in the spring with an herbicide, but organic systems have traditionally relied on tillage or mowing for termination. These termination methods are not ideal, as tilling can have negative effects on soil health, as discussed earlier, and mowing requires energy-intensive power take-off (PTO)-driven equipment (Ashford and Reeves, 2003). In addition, mowing leaves the cover crop in small pieces that decompose rapidly, and may result in less weed suppression than if the cover crop remained intact (Creamer and Dabney, 2002). A relatively new method for cover crop termination that leaves the cover crop intact and allows for season-long weed control without tillage is roller-crimping. The roller-crimper, first developed in South America (Derpsch et al., 1991, as cited in Mirsky et al., 2013), and popularized by the Rodale Institute in Kutztown, PA, kills cover crops by rolling them down with a large steel cylinder, providing a thick layer of persistent mulch that can suppress weeds. Roller-crimping requires tenfold less energy than a rotary mower (Ashford and Reeves, 2003), and is much faster, and therefore less expensive and labor-intensive than mowing.

The roller-crimper is the key to a system that has been referred to as cover crop-based, organic rotational no-till (Mirsky et al., 2012). In this system, cash crops are no-till planted into cover crops killed with a roller-crimper. It is called “rotational” no-till because tillage is used prior to seeding the cover crop for long-term suppression of perennial weeds (Mirsky et al., 2012). Organic rotational no-till systems have been shown to reduce fuel and labor requirements by 27 and 31%, respectively, compared to traditional organic management (Mirsky et al., 2012; Ryan, 2010). In addition, rolled cover crop mulches provide very effective in-season weed suppression. Cereal

rye is especially effective as a rolled mulch: it can suppress weeds by weakening germination cues (via reducing light and temperature fluctuations), interfering physically with weed emergence, immobilizing nitrogen (resulting from the high C:N ratio of the residue), and releasing allelopathic metabolites that cause phytotoxin inhibition (Mirsky et al., 2013). Despite these advantages, planting cereal rye before soybean does have potential risks, such as increasing pest problems (Stinner and House, 1990), and depleting soil moisture at the beginning of the growing season (Liebl et al., 1992; Wagner-Riddle et al., 1994), which can adversely affect soybean germination and yield (Liebl et al. 1992; Wells et al., 2016). Rolled cereal rye can also impede seed placement (Clark et al., 2017; Wagner-Riddle et al., 1994).

The aim of this experiment was to assess cereal rye management strategies prior to organic soybean for their impact on soil health, weed suppression, crop yield, and profitability. The treatments included: ‘No cover’ – no cover crop seeded; ‘Plow down’ – cereal rye plowed in at jointing stage; ‘Ryelage’ – cereal rye harvested at boot stage and stubble plowed in; and ‘Roll down’ – cereal rye roller-crimped at anthesis. We hypothesized that, depending on management method, integrating a cereal rye cover crop prior to soybean would improve soil health, maintain weed suppression and soybean yield, and improve profitability compared to a no cover crop control.

MATERIALS AND METHODS

Site Description

This experiment was conducted in 2015 and 2016 at two locations at Musgrave Research Farm near Aurora, NY (42.73°N, 76.65°W). The soil type at the 2015 site was 77% Lima silt loam, (fine-loamy Oxyaquic Hapludalf) with 0 to 3% slopes, and

22% Honeoye silt loam (fine-loamy Glossic Hapludalf) with 2 to 8% slopes (Soil Survey Staff 2016). The previous crop at the 2015 site was grain corn. The soil type at the 2016 site was 58% Lima silt loam with 3 to 8% slopes, 25% Honeoye silt loam with 2 to 8% slopes, and 17% Lima silt loam with 0 to 3% slopes (Soil Survey Staff 2016). The previous crop at the 2016 site was soybean, though it was planted late (July 30), mowed, and moldboard plowed in September before it had reached a height of 15 cm. The soils at the two field sites were similar, with pH ranging from 7.4 – 7.5 and organic matter ranging from 2.7 – 2.8% (Appendix A).

Experimental Design

The experiment was arranged in a spatially-balanced, randomized complete block design, with four replications (van Es et al., 2007). Treatment plots measured 9 × 21 m. Four treatments were compared: 1) ‘No cover’ (no cereal rye was seeded), 2) ‘Plow down’ (cereal rye was moldboard plowed at jointing stage) 3) ‘Ryelage’ (cereal rye was harvested for fodder at boot stage and stubble was moldboard plowed before planting soybean), and 4) ‘Roll down’ (cereal rye was roller-crimped).

Field Operations

In the fall prior to each field season, organic amendments were applied to all plots to ensure adequate cereal rye growth (Tables 1 and 2). In 2014, manure solids (2.0-0.4-0.7) were applied at 22.4 Mg ha⁻¹ and in 2015 poultry litter (Kreher’s 5-4-3) was applied at 1.4 Mg ha⁻¹. After fertilization and moldboard tillage, the three cover crop treatments were drill-seeded with cereal rye (*Secale cereale*, L., cv. ‘Aroostook’) at 200 kg ha⁻¹. In the spring of each year, the ‘Plow down’ treatments were moldboard plowed at Zadoks 34-35 (Zadoks et al., 1974), the ‘Ryelage’ treatments were harvested at Zadoks 53-57 and plowed 7-13 days later. In 2015, the ‘No cover’

treatment was moldboard plowed at the same time as the 'Ryelage' treatment. However, in 2016, the 'No cover' treatment was plowed at the same time as the 'Plow down' treatment, due to unwanted cereal rye growth (ranging from 73 to 912 kg ha⁻¹). The 'Roll down' plots were roller-crimped at Zadoks 71 in 2015 and Zadoks 65-67 in 2016. Both years, the roller-crimper was front-mounted and filled with water to a total mass of 1195 kg, and cereal rye was rolled perpendicular to the direction it was drilled, which is a recommended practice for increasing ground cover and weed suppression.

All plots except the 'Roll down' plots were disked and cultimulched prior to soybean planting. In 2015, soybeans were planted directly after the tilled plots were disked and cultimulched, and the 'Roll down' plots were rolled. In 2016, however, soybeans were planted 8 days after disking and cultimulching, and 5 days after rolling, due to dry conditions. 'Viking 2299' (maturity group 2.2) and 'Viking 2399' (maturity group 2.3) soybeans were planted in 2015 and 2016, respectively, into all treatments in 76 cm rows at a target rate of 625,000 seeds ha⁻¹. In 2015, this rate was achieved, but in 2016, a different planter was used, which resulted in a slightly higher planting rate (767,000 seeds ha⁻¹). Soybeans were inoculated with *Bradyrhizobium japonicum*.

Due to extremely dry conditions in 2016, irrigation was determined necessary. On July 7 and July 8, soaker hoses were used to apply 568 L of water to the middle 7.6 m of all 12 rows in each plot. This was equivalent to a 0.64-cm rainfall in all plots. To ensure that irrigation was even across all treatments and all plots, the rate of water released from each soaker hose was measured and confirmed to be equal. The twelve hoses were then placed in each plot and allowed to run for an interval of time calculated based on the targeted 0.64-cm rainfall. In 2015, the three tilled treatments were cultivated five times in June and July, and the 'Roll down' treatment was cultivated with a high-residue cultivator in late July. In 2016, all tilled plots were tine-

Table 1. Schedule of field operations in 2014-2015.

Field operation	Year	Date	Equipment
Manure solids spreading began, continued to 9/22	2014	Sept 1	
Moldboard plowed entire field		Sept 24	Kverneland 125 4-bottom plow
Tandem disked entire field		Sept 25	John Deere 637
Cultimulched entire field		Sept 29	John Deere 950
Drill-seeded cereal rye in 'Ryelage', and 'Plow down', and 'Roll down' treatments		Oct 7	John Deere 1590 no-till drill
'Plow down' treatment moldboard plowed at Zadoks 37	2015	May 7	Kverneland Model A 3-bottom plow
'Ryelage' treatment harvested at Zadoks 53-57		May 15	John Deere 972 Forage Chopper
'No cover' and 'Ryelage' treatments moldboard plowed		May 22	Kverneland Model A 3-bottom plow
All tilled plots disked and cultipacked		June 4	John Deere 637
'Roll down' treatment roller-crimped at Zadoks 71		June 4	I&J MFG Roller-crimper
Planted soybeans		June 4	John Deere 7200 Conservation Tillage Planter, 4-row
Soybean cultivation in all plots except 'Roll down'		June 20	Belly-mount, 2-row unit
Soybean cultivation in all plots except 'Roll down'		June 25	John Deere 825 4-row cultivator
Soybean cultivation in all plots except 'Roll down'		July 6	John Deere 825 4-row cultivator
Soybean cultivation in all plots except 'Roll down'		July 13	John Deere 825 4-row cultivator
Soybean cultivation in all plots except 'Roll down'		July 17	John Deere 825 4-row cultivator
High-residue cultivation in 'Roll down'		July 27	John Deere 825 High Residue Cultivator
Interseeded hairy vetch into soybeans		July 28	Penn State Interseeder
Harvested soybeans		Oct 12	Almaco SP20 2-row combine

Table 2. Schedule of field operations in 2015-2016.

Field operation	Year	Date	Equipment
Moldboard plowed entire field	2015	Sept 9	Kverneland 5-bottom plow
Tandem disked entire field		Sept 9	John Deere 4320 and John Deere disc
Fertilized with poultry litter		Sept 16	Gandy drop spreader
Cultimulched entire field		Sept 18	John Deere 950
Drill-seeded cereal rye in 'Ryelage', and 'Plow down', and 'Roll down' treatments		Sept 18	John Deere 1530 no-till drill
'Plow down' and 'No cover' treatments moldboard plowed at Zadoks 43-45	2016	Apr 22	Kverneland Model A 3-bottom plow
'Ryelage' treatment harvested at Zadoks 52-55		May 4	John Deere 972 Forage Chopper
'Ryelage' treatment moldboard plowed		May 17	Kverneland Model A 3-bottom plow
All tilled plots disked and cultipacked		May 23	John Deere 637
'Roll down' treatment roller-crimped at Zadoks 65-67		May 26	I&J MFG Roller-crimper
Planted soybeans		May 31	John Deere 1750 maxEmerge XP Planter, 6-row
Tine weeding		June 24	RabeWerk Tine Weeder with 85 degree bent tines
Irrigation		July 7-8	
Soybean cultivation in all plots except 'Roll down'		July 13	John Deere 825 4-row cultivator
Soybean cultivation in all plots except 'Roll down'		July 28	John Deere 825 4-row cultivator
Interseeded hairy vetch		July 28	Penn State Interseeder
Harvested soybeans		Oct 19	Harvested by hand

weeded in late June and cultivated twice in July. There was no high-residue cultivation in the 'Roll down' treatment in 2016, as limited weed growth in the dry conditions made it unnecessary. In both years, hairy vetch (*Vicia villosa* Roth) was interseeded in late July into the three cover-crop treatments in preparation for another experiment the following growing season.

Weather Data Collection

Weather data were collected at a meteorological station at the research site (Northeast Regional Climate Center, 2017). Air temperature data were summarized by taking the mean of daily temperature averages in each growing season (June 1 – September 31 for soybeans, and October 1 through May 31 for cereal rye). Precipitation data were summarized by monthly accumulated precipitation, as well as by total accumulation over the course of the soybean growing season (May 1 – October 20). Air temperature and precipitation data were compared to a 30-year (1981 – 2010) average calculated by the National Climate Data Center (Northeast Regional Climate Center, 2017).

Soil Sampling and Analyses

Sampling. Soil was sampled on August 5, 2015 and August 8, 2016. From each 9 × 21 m plot, four 15-cm-diameter cores were taken to a 15-cm depth for aggregate stability testing. Sixteen and twenty 2.5-cm-diameter cores per plot were taken in 2015 and 2016, respectively, to a depth of 15 cm, for potentially-mineralizable nitrogen (PMN), permanganate-oxidizable carbon (POXC), and soil respiration testing. Cores taken within each plot were mixed thoroughly. Approximately 40 g of soil material from each plot was sieved to 2 mm, ~ 32 g of which was used for in-field PMN preparations (described below). The remaining sieved soil material was weighed, dried at 60°C for three days, and weighed again to calculate the moisture content for PMN analysis.

Unsieved soil material was stored in a cooler until transferred to double paper bags for air drying. Additional soil samples were taken in 2016 on May 24, May 31, June 7, and June 15 for nitrate and ammonium analysis. Sampling for this analysis consisted of ten 2.5-cm-diameter cores per plot, taken to a 15-cm depth. Soil health analyses (detailed descriptions below) were conducted according to the standard operating procedures for the Cornell Comprehensive Assessment of Soil Health (Schindelbeck et al., 2016).

Soil respiration. Air-dried soil was sieved to 8 mm. Subsamples (20.00 g) of each sample were weighed into aluminum tins, which were perforated with 9 pin-holes through the bottom. Each tin was placed on top of filter paper at the bottom of a standard 1 pint mason jar. A trap consisting of a plastic tripod ‘pizza stool’ with a 10-ml beaker secured on top was placed in each jar, and the beaker was filled with an alkaline CO₂-trapping solution (9 ml of 0.5 M potassium hydroxide (KOH)). Distilled, deionized (DI) water (7 ml) was pipetted into each jar so that the filter paper would wick it up. The jars were tightly sealed and incubated for 4 days. The electrical conductivity of the KOH in the trap declines linearly with increasing CO₂, so respiration is calculated based on the electrical conductivity of the KOH after the incubation, and a standard curve (Zibilske, 1994). Values from this test were converted to mg CO₂ g⁻¹ week⁻¹ to allow for comparison with other research.

Permanganate-oxidizable carbon (POXC). Air-dried soil was sieved to 2 mm. Subsamples (2.5 g) of each sample was measured into 50-ml centrifuge tubes, and 20 ml of 0.02 M potassium permanganate (KMnO₄) solution (dark purple in color) was added to each tube. The tubes were shaken for exactly two minutes to oxidize the active carbon in the samples – a process that causes the purple color to become lighter.

The sample tubes were then allowed to settle for eight minutes, after which 0.2 ml of the solution in each tube was pipetted into tubes filled with 20 ml of distilled water. Absorbance was measured at 550 nm, and values were interpreted by comparing with a calibration curve, created from a standard dilution series of KMnO_4 , and then used to calculate POXC in units of mg carbon kg^{-1} (Weil et al., 2003).

Potentially Mineralizable Nitrogen (PMN). The day before sampling, four centrifuge tubes were prepared for each soil sample: two with 40 ml of 2.0 M potassium chloride (KCL) and two with 10 ml of DI water. Tube weights were recorded. At the time of sampling, soil from each sample was sieved to 2 mm, and ~8 g of soil was added to each of the four centrifuge tubes. Tubes were stored in coolers and were weighed upon return to the lab to calculate the exact amount of soil added. The samples with KCl were placed in the shaker for one hour, and the DI water tubes were purged with nitrogen gas and placed in the incubator at 30°C for one week. Extractions were taken from the KCl tubes the following morning. After one week, 30 ml of 2.67 M KCl was added to the tubes with DI water, tubes were placed in the shaker for one hour, and extractions were taken (Drinkwater et al., 1996). After extractions were taken, they were stored in the freezer, and later analyzed for ammonium, using an autoanalyzer (BRAN+LUEBBE, method G-145-95, BRAN+LUEBBE, Norderstedt, Germany), and following EPA method 350.1 (USEPA, 1983). PMN is the amount of ammonium mineralized over the course of one week, so the PMN values were calculated by subtracting the amount of ammonium in the KCl extractions that were taken immediately from the amount of ammonium in the KCl extractions that were taken after samples were incubated in DI water for one week.

Nitrate and ammonium. A small subsample of soil from each treatment was weighed at field moisture, immediately following sampling, and dried overnight at 105°C for calculating percent moisture. The rest of the soil samples were dried at 50°C overnight. The following day, the samples were mechanically crushed and passed through a 2-mm mesh screen. Subsamples (2 g) of each sample were weighed into crucibles and placed in the oven at 110°C for one hour to calculate residual moisture content. Subsamples (5 g) from each sample, one replicate, and one quality control sample were weighed and placed into flasks. One flask was left empty. Carbon (1 g) and 50 ml of 2 M KCl was added to each flask, and flasks were shaken on an automatic shaker for one hour. At the end of the hour of shaking, contents from flasks were poured into the funnels lined with filter paper, and allowed to drain into test tubes (Griffin et al., 2009). Test tubes were then stored in the refrigerator for less than one week until the KCl extractions could be analyzed for nitrate and ammonium, using an autoanalyzer (BRAN+LUEBBE, method G-109-94 and G-145-95, BRAN+LUEBBE, Norderstedt, Germany), and EPA methods 353.2 and 350.1, respectively (USEPA, 1983).

Aggregate stability. Air-dried soil was sieved to 8 mm. Aggregates between the sizes of 0.25 mm and 2.0 mm were further sieved out for analysis. A single layer of aggregates from each sample was sprinkled on a 0.25-mm sieve, and sieves were placed below a rainfall simulator for five minutes, receiving 12.5 mm of water, amounting to 1.9 J of energy. The soil that slaked through the sieves (aggregates that failed) were collected, the remaining stable aggregates were washed through the sieves, and any stones remaining on the sieves were collected. Wet aggregate stability was then calculated by dividing the weight of the stable aggregates (found by

subtracting the dry weight of the slaked soil and stones from the dry weight of the total sample) by the weight of the total sample (Schindelbeck et al., 2016).

Infiltration. Cornell Sprinkle Infiltrimeters (Ogden et al., 1997) were used in the field on August 10, 2015 to measure infiltration. A metal ring (24 cm diameter) with a hole on one sidewall was lightly pounded into the ground until the bottom of the hole was level with the ground. A tube was attached to the hole and soil was excavated so as the tube was oriented downwards. The target simulated rainfall rate was 15 cm hr⁻¹, although the actual rate ranged from 11 to 20 cm hr⁻¹. The water level in the infiltrimeter was recorded every minute to keep track of the simulated rainfall rate, and time to first runoff was recorded. These numbers were used to calculate sorptivity, which aims to normalize time-to-runoff so that it is independent of rainfall rate. Sorptivity was calculated as follows, according to Kutilek (1980):

$$S = (2T_{ro})^{0.5} * r$$

S=sorptivity; T_{ro}= time to runoff; and r = rainfall rate

In 2016, infiltration was attempted on June 12, but conditions were too dry to get runoff. Infiltration was completed successfully on July 19 and 20 (split over two days), and again on August 15. Due to dry conditions, the 2016 target simulated rainfall rate was 24 cm hr⁻¹ (actual rate ranged from 10 to 39 cm hr⁻¹).

Soil Volumetric Water Content. A soil moisture probe (HH2 moisture meter type, Delta-T Devices Ltd., Cambridge, UK) was used weekly in 2015 to measure soil volumetric water content (VWC) from August 10 to October 8. Soil VWC was

measured between soybean rows in the top 6.5 cm of soil. In 2016, soil VWC was measured biweekly from May 31 to July 12, and weekly until September 28.

Soil Temperature. Soil temperature data loggers (Watchdog B-Series, Field Scout Spectrum Technologies, Plainfield, IL) were placed 8 cm below soil surface, in between soybean rows. In 2015, data loggers were in the ground from August 5 to October 12, and in 2016 they were in the ground from April 22 to November 4. Data loggers recorded temperature every minute. Data was summarized by weekly average, minimum, and maximum for analysis.

Crop and Weed Sampling

Cover Crop Biomass. Cover crop biomass was measured in each plot by clipping cereal rye in one 0.5 m² quadrat prior to termination: May 7 and April 22 for the ‘Plow down’ treatment, May 15 and May 4 for the ‘Ryelage’ treatment, and June 4 and May 26 for the ‘Roll down’ treatment in 2015 and 2016, respectively. Cereal rye in the ‘Plow down’ and ‘Roll down’ treatments was clipped at the soil surface, and cereal rye in the ‘Ryelage’ treatment was clipped at 10 cm above the surface, to simulate a forage harvester. Plant material was placed in paper bags, dried at 65°C for 1-2 months, and then weighed.

Soybean Density and Weed Biomass. Soybean stand density and weed biomass were measured on September 3, 2015 and September 6, 2016 in 0.5-m² quadrats at two locations per plot. Common ragweed (*Ambrosia artemisiifolia*, L.) was weighed separately from other weeds due to its previously reported prevalence in cover crop based, organic no-till soybean systems in the northeast (Liebert, 2017; Mirsky et al., 2013; Nord et al., 2012). This prevalence is due to common ragweed’s early

emergence; the roller-crimper does not control emerged seedlings (Mirsky et al., 2013). Weeds were dried in paper bags for at least 72 hours at 65°C, and weighed.

Soybean Yield. In 2015, soybeans from four 15.2-m rows in the middle of each plot were harvested on October 12, with a two-row plot combine (Almaco SP20, Nevada, IA). In 2016, due to increased growth of the interseeded hairy vetch, it was not possible to use a combine for harvest, so soybean harvest was instead done by hand with electric clippers on October 19. Four 2.7-m rows were harvested per plot, and soybeans were threshed with the same combine used in 2015 (Almaco SP20, Nevada, IA). Weight and moisture of harvested soybeans were recorded. For both years, soybean yield was adjusted to 13% moisture.

Economic Analysis

An economic analysis was conducted to quantify the difference in variable costs, return over variable costs, and labor requirements between each treatment. Variable costs included cereal rye seed (cv. ‘Aroostook’, Ernst Conservation Seeds Inc.), soybean seed (cv. ‘Viking 2299’, Lakeview Organics), and custom rates for field operations. Soybean seed costs in the economic analysis were based on the cost of ‘Viking 2299’ at 625,000 seeds ha⁻¹. There were a few differences between actual field operations and those included in the economic analysis. First, although amendments were applied to all plots prior to seeding cereal rye, this operation was excluded from the economic analysis, as it would be unlikely for a grower to follow such practices. Second, tillage was excluded from the ‘No cover’ treatment, as this more accurately represents standard practices when a cereal rye cover crop is not seeded. Third, although the ‘Ryelage’ treatment was harvested with a forage chopper, the cost of harvesting the cereal rye in the economic analysis was based on the costs of mowing,

raking, and baling. Fourth, the cost of roller-harrowing was substituted for tine-weeding.

Custom rates for most field operations, with the exception of roller-crimping, and high-residue cultivation, came from a single source (The Pennsylvania State University, 2016). These rates include the cost of hiring machinery with fuel and operator, and exclude the cost of seed, fertilizer, and other materials. The cost of roller-crimping was estimated at \$9.88 ha⁻¹, based on expert opinion (A. Frankenfield, personal communication, 2016), and a separate source was used for the cost of high-residue cultivation (\$31.27 ha⁻¹), which took place once in the 'Roll down' treatment in 2015 (Stein, 2016).

Income sources consisted of soybean and ryelage farm gate sales, which were calculated based on the yield of soybean and ryelage from the experimental plots. Soybeans (organic feed-grade) were valued at the 2015 national average of \$0.87 kg⁻¹ (\$23.75 bu⁻¹) (USDA-AMS, 2016). Ryelage value was determined with the PennState Extension Feed Value Calculator (PennState Extension, 2016), based on forage quality data from ryelage samples that we collected at the time of harvest and that were analyzed by Dairyland Laboratories Inc. (Arcadia, WI). The value of the ryelage in our plots ranged from \$56.29 to \$57.71 Mg⁻¹. The above-stated costs and the income sources were used to calculate return above variable costs for each treatment.

Labor required for each treatment were also calculated. Labor hours for most operations, with the exception of baling and high-residue cultivation, came from a single source (Stein, 2016). Labor hours for baling (Lazarus, 2016) and high-residue cultivation (Stein, 2009) were from separate sources.

Statistical Analysis

Mixed model analysis of variance (ANOVA) was completed in R version 3.2.2 (R Core Team, 2015) to test treatment effects in soil, agronomic, and economic data. Treatment, year, and their interaction were included as fixed effects, and block was included as a random effect. A random block \times year interaction was included if it explained any of the variance in the model. If there was a significant ($P < 0.05$) treatment \times year interaction, the interaction was included in the model, and treatment means were compared within year using Tukey's pairwise comparison. If there was a significant treatment effect but no significant interaction effect, the interaction was excluded from the model and treatment means were pooled over years and compared with Tukey's pairwise comparison of means. If variances were considerably different between the two years, data from each year was analyzed separately. Soil nitrate, weed biomass, and soybean density data were log transformed for analysis, and back-transformed means are presented. Significant differences are shown in bar charts with letters, and similar letters above bars indicate no significant difference ($P > 0.05$).

RESULTS AND DISCUSSION

Weather Conditions

Weather during the two experimental years when the experiment was conducted differed dramatically. Differences in spring precipitation, especially for the month of soybean planting, illustrate that the optimum cereal rye management practice might depend on weather conditions. In 2015, accumulated precipitation in May and June was 14.1 and 20.3 cm, respectively – nearly double the 30-year (1981 – 2010) average of 8.0 and 9.6 cm. In 2016, accumulated precipitation for the same two months was

only 6.3 and 2.8 cm. In July, accumulation in 2015 was slightly lower than the 30-year average, at 7.1 cm compared to 8.9 cm, but in 2016, July accumulation was still far below normal, at 4.8 cm. In August, 2015 accumulated precipitation was lower than normal at 3.5 cm compared to 8.0 cm, but higher than normal in 2016, at 11.6 cm. Overall, accumulated precipitation throughout the soybean growing season was much higher than normal in 2015, and much lower than normal in 2016 (Figure 1). Soybeans were irrigated in July of 2016, as described above.

Temperatures during the cereal rye growing season (October 1 – May 31) were lower than the 30-year average of 3.8°C in 2015, with an average of 2.1°C, and higher than the average in 2016, with an average of 4.8°C. Temperatures during the soybean growing season (June 1 – September 31) were comparable to the average in both years (19.3 and 20°C in 2015 and 2016, respectively, compared to the average of 19.7°C).

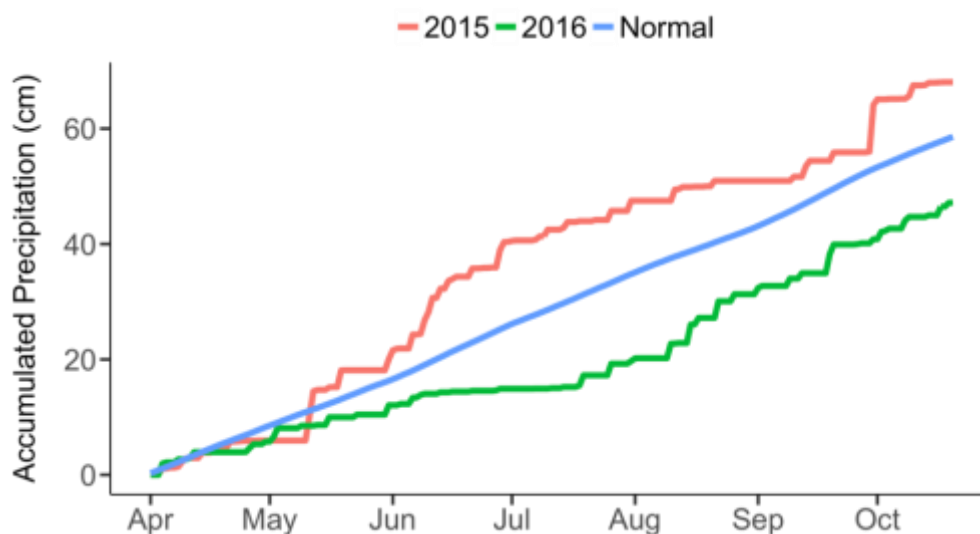


Figure 1. Accumulated precipitation for 2015 and 2016, compared to the 30-year (1981 – 2010) climate average, calculated by the National Climate Data Center (Northeast Regional Climate Center 2017).

Soil Indicators

Soil Respiration. Soil respiration is a measurement of the CO₂ evolved from soil during a set duration of time, and is a useful indicator of the overall biological activity of the soil (Moebius-Clune et al., 2016). In this experiment, both treatment and year affected soil respiration. Soil respiration values were greater in 2015 (1.31 mg CO₂ g⁻¹ week⁻¹) than 2016 (0.79 mg CO₂ g⁻¹ week⁻¹), most likely because of the greater precipitation in 2015, which likely stimulated soil microorganisms. No treatment × year interaction was observed, so treatment means were analyzed pooled over years (Table 3). The ‘Roll down’ treatment had higher respiration than the ‘No cover’ treatment. This difference is quite interesting given that cereal rye was only grown for one season.

A positive relationship was observed between the duration of cereal rye growth and the amount of CO₂ evolved. This is congruent with other studies that have reported the effects of cover cropping on soil respiration. Hurisso et al. (2016) found that C mineralization (i.e. soil respiration) is associated with practices that encourage organic matter mineralization, such as the addition of cover crops, and Fernandez et al. (2016) found that, at one of three sites, there was twice as much soil respiration in plots with cereal rye than in a no-cover crop control. It is possible that the lack of tillage during the growing season in the ‘Roll down’ treatment could also explain the higher soil respiration. Although Hurisso et al. (2016) argue that tillage leads to enhanced C mineralization (i.e. respiration), other studies have found higher C mineralization in no-till compared to conventional-till systems (Perez-Brandan et al., 2012; Vargas et al., 2009). Perez-Brandan et al. (2012) reason that the increased respiration in the no-till systems is likely due to the accumulation of residue that creates a more temperature- and moisture-moderating environment that is more

conducive to microbial activity (Perez-Brandan et al., 2012). These factors may be another reason for the higher respiration in the ‘Roll down’ treatment.

Permanganate-Oxidizable Carbon (POXC). Permanganate-oxidizable carbon measures the pool of labile organic carbon, and has been shown to be more sensitive to changes in management than total organic carbon (Weil et al., 2003). In addition, POXC is often correlated with other soil quality indicators, including substrate-induced and basal respiration, aggregate stability, and microbial biomass (Weil et al., 2003). Here, POXC did not differ between treatments or between years, and there was no treatment \times year interaction. POXC levels were low across the board, scoring only 30-35 out of 100 on the Cornell Soil Health scale (Moebius-Clune et al., 2016).

The low POXC can be explained by the history of tillage in both sites, as POXC has been shown to be correlated with management practices that build soil organic matter (Hurisso et al., 2016), and tillage typically stimulates decomposition of organic matter. Hurisso et al. (2016) noted that tilled fields, and even fields that have recently been converted to no-till, as in our ‘Roll down’ treatment, have a higher correlation with mineralizable C (i.e. soil respiration) than POXC, which is supported by the fact that we saw differences in soil respiration but not in POXC. The lack of differentiation of POXC between treatments could also be due to the short duration of the treatments imposed. Research by Idowu et al. (2009), indicated that POXC might not be a good indicator for measuring short-term changes in management. In short-term experiments, different management practices are more likely to cause a difference in soil respiration than in POXC, because C mineralization can be influenced in one season, while building soil organic matter takes longer.

Table 3. *P*-values and treatment means for soil health, agronomic, and economic measurements are presented. When an interaction was not significant, it was removed from the model and data were re-analyzed without the interaction. Treatment means are presented with SE immediately to the right, in brackets, followed by letters that compare treatment means. Similar letters indicate no significant difference ($P > 0.05$). When means are presented by year, letters are lower case for 2015 and uppercase for 2016.

Measurement	Treatment		Treatment × Year	Year	No cover	Plow down	Ryelage	Roll down
	Treatment	Year						
	P-values							
Respiration (mg CO ₂ g ⁻¹ week ⁻¹)	0.027	< 0.001		2015, 2016	0.949 (0.101) b	1.065 (0.070) ab	1.030 (0.111) ab	1.164 (0.145) a
POXC§ (mg kg ⁻¹)	0.767	0.893		2015, 2016	429 (78)	447 (22)	434 (24)	455 (20)
PMN§ (µg N g ⁻¹ week ⁻¹)	0.052	0.05	0.042	2015	4.76 (0.29) a	3.81 (1.02) a	3.57 (0.72) a	4.93 (0.95) a
				2016	3.76 (0.83) B	7.66 (1.13) A	4.02 (0.69) B	6.17 (0.65) AB
Aggregate stability (%)	0.737	0.045		2015, 2016	43.8 (4.1)	45.9 (4.2)	43.3 (3.8)	46.1 (5.1)
Sorptivity (mm min ^{-0.05})	0.053	0.002¶		2015, 2016	9.5 (1.4) b	11.5 (2.1) ab	13.1 (1.6) ab	16.9 (3.5) a
Cereal rye biomass (kg ha ⁻¹)	< 0.001	< 0.001		2015, 2016	NA	1426 (280) b	1978 (198) b	5123 (472) a
Weed biomass (kg ha ⁻¹)#	0.003	0.987		2015, 2016	21.3 b	14.3 b	18.6 b	356.8 a
Soybean density (10,000 plants ha ⁻¹)#	< 0.001	< 0.001	< 0.001	2015	48.2 a	47.6 a	48.1 a	47.6 a
				2016	73.4 A	74.2 A	56.6 B	41.4 C
Soybean yield (kg ha ⁻¹)##	0.020			2015	2731 (168) ab	3053 (90) a	3022 (81) ab	2637 (66) b
	0.030			2016	2294 (150) A	1947 (282) AB	2203 (236) AB	1302 (302) B
Return over variable costs (USD ha ⁻¹)##	0.002			2015	1780 (147) b	1773 (79) b	2343 (43) a	1655 (58) b
	0.002			2016	1490 (131) AB	899 (246) BC	1954 (162) A	519 (264) C

†POXC = Permanganate-Oxidizable Carbon; PMN = Potentially Mineralizable Nitrogen

‡ For sorptivity, the effect measured was date, not year, as sorptivity was measured over three dates.

§ Weed biomass and soybean density were log-transformed for analysis, so means presented here are back-transformed, and there are no standard errors presented.

¶ For soybean yield and return over variable costs, years were analyzed in separate models due to unequal variances (see standard errors). Soybean yield was adjusted to 13% moisture.

Potentially Mineralizable Nitrogen (PMN). Potentially mineralizable nitrogen tests how much nitrogen is mineralized during an incubation period, and is an indicator of both microbial activity (immobilization-mineralization) and labile organic nitrogen (Drinkwater et al., 1996). Soils with higher levels of organic matter have more organic nitrogen that can be mineralized. However, organic matter also can lead to nitrogen immobilization. The balance between immobilization and mineralization is regulated by the C:N ratio of the organic matter. When the C:N ratio is high, there is net immobilization, but as the C:N ratio decreases and microorganisms die off, there is net mineralization.

In this experiment, there was a treatment \times year interaction effect on PMN, so PMN was analyzed separately by year (Table 3). No differences among treatments were observed in 2015; however, the mean PMN for the 'Plow down' treatment in 2016 was almost double the means of the 'No cover' and 'Ryelage' treatments. As soil properties between the two fields were similar, the greater differentiation between treatments in 2016 was most likely a result of weather. In 2015, the greater precipitation most likely caused mineralization to happen earlier in the season. By the time samples were taken in August, much of the organic N at the 2015 site had probably already been mineralized. In 2016, however, the lack of precipitation could have slowed mineralization, so that at the time of sampling in August, more organic N was still available for mineralization compared to 2015.

The fact that PMN was higher in the 'Plow down' treatment compared to the 'No cover' and 'Ryelage' treatments in 2016 indicates that there was either more organic matter or higher N-content organic matter in that treatment. Although the 'Plow down' treatment did have the highest amount of cereal rye aboveground biomass incorporated, the roots did not have as much time to develop in that treatment as they did in the 'Ryelage' and 'Roll down' treatments. Thus, it is not clear if there

was more organic matter in that treatment. In terms of N-content, since the biomass in the 'Plow down' treatment was incorporated earliest, it had the lowest C:N ratio, meaning a higher potential for mineralization. However, this mineralization was probably slowed by lack of moisture, as mentioned above. Assuming mineralization was slowed equally in the 'Plow down' and 'Ryelage' treatments, it could be argued that the higher PMN in the 'Plow down' treatment resulted from the delayed mineralization of the higher-N-content biomass.

Nitrate. To better understand the effect of the treatments on soil nitrogen levels, soil samples were collected in the spring during the second year of the experiment and analyzed for soil nitrate. In spring of 2016, soil nitrate levels were affected by a treatment \times date interaction, so sampling dates were analyzed separately. The 'No cover' treatment had higher soil nitrate levels than all three of the cover crop treatments for all four sampling dates (Figure 2). In addition, nitrate levels became more differentiated between treatments over time. On May 24, the 'Plow down' treatment had higher nitrate levels than the other two treatments. At this point, the cereal rye in the 'Plow down' plots had been tilled in a month prior (on April 22), and the cereal rye stubble in the 'Ryelage' treatment had been tilled in a week prior (on May 17). On May 31, there was no difference in nitrate levels between the 'Plow down' and 'Ryelage' treatments, but they both had levels higher than the 'Roll down' treatment. On June 7, nitrate levels in all four treatments differed from one another, with 'No cover' having the highest level, 'Plow down' coming in second, 'Ryelage' third, and 'Roll down' fourth. This distribution of nitrate levels between treatments remained the same on June 15.

Consistently higher nitrate levels in the 'No cover' treatment can be explained by the lack of cereal rye taking up nitrogen in the spring. The increasing levels of nitrate over time in the 'No cover' treatment is most likely the result of the

mineralization and nitrification of soil organic matter. In the ‘Ryelage’ and ‘Plow down’ treatments, slower rates of SOM mineralization and nitrification could indicate immobilization caused by the decomposition of cereal rye. This immobilization seems to be playing an even larger role in the ‘Roll down’ treatment, probably due to the greater amount of biomass and higher C:N ratio of that biomass. Immobilization from crimped cereal rye has also been noted by Clark et al. (2017), and by Wells et al. (2013; 2017). Interestingly, Wells et al. (2013) suggest that the reduction in plant-available nitrogen caused by cereal rye has potential for regulating weeds, with minor reduction in soybean yield.

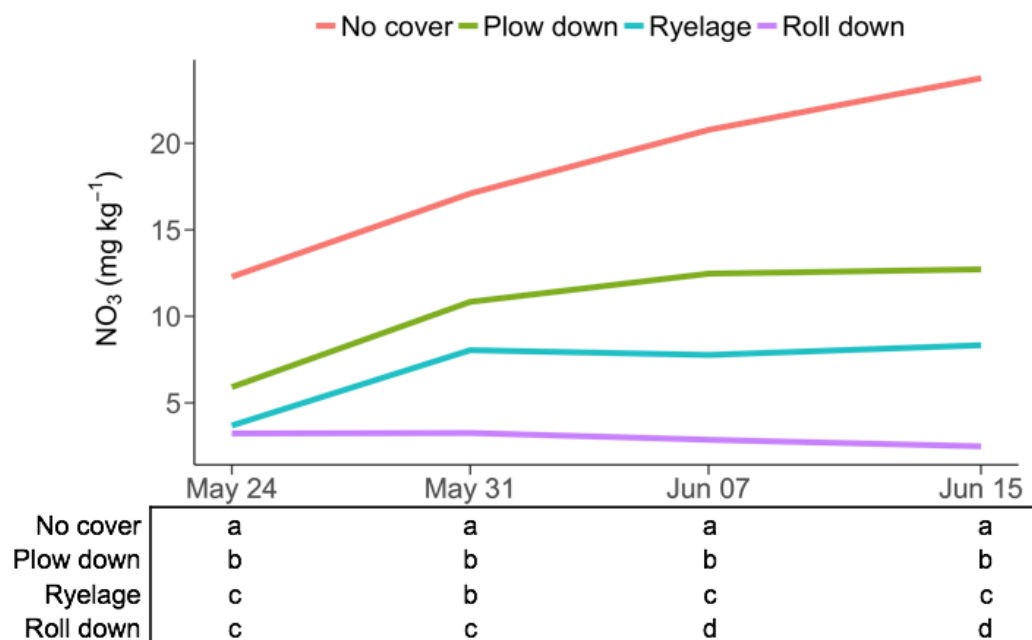


Figure 2. Soil nitrate by treatment at four dates in 2016. Similar letters indicate no difference between treatments within each date ($P > 0.05$).

Ammonium. Ammonium levels in spring 2016 did not differ between treatments, but did differ between dates ($P < 0.01$). The two later dates, June 7 and June 15, had less ammonium (2.7 and 3.1 mg kg⁻¹, respectively) than the first date, May 24 (4.4 mg kg⁻¹).

¹). The decrease in ammonium in all treatments can be explained by increasing temperatures, which can cause both nitrification and immobilization to increase, due to increased microbial activity. For ammonium levels to have decreased while nitrate levels increased in the 'No cover', 'Plow down', and 'Ryelage' treatments, nitrification must have been happening faster than mineralization. In the 'Roll down' treatment, the most probable explanation for decreasing ammonium is immobilization, but it could also be the result of nitrification with little to no mineralization to replenish the ammonium.

Aggregate Stability. Wet aggregate stability is a robust test of soil physical health that is related to biological and chemical processes (Idowu et al., 2009). Aggregate stability testing showed no significant differences between treatments, and no significant year or treatment \times year interaction effect (Table 3). The lack of differentiation between treatments is most likely due to the short duration of the treatments. The tillage in the 'Plow down' and 'Ryelage' treatments could also be masking the effect of cereal rye on aggregate stability. Aggregate stability has indeed been found to increase with incorporation of cereal rye into no-till rotations (Villamil et al., 2006; Steele et al., 2012), and with lack of tillage (Idowu et al., 2009; Al-Kaisi et al., 2014; Perez-Brandan et al., 2012) in the long term. On the other hand, one short-term study (Mochizuki et al., 2008) reported that rolling cereal rye and leaving it on the surface as mulch for just one season resulted in higher aggregate stability compared to treatments with only cereal rye stubble on the surface. More research is needed on the short-term effects of various cereal rye management methods on aggregate stability.

Sorptivity. Water infiltration is important to drainage, moisture retention, and run-off and erosion reduction. Generally, cover crops and reduced tillage have been found to increase the rate of water infiltration (Dabney et al., 2001; Sainju and Singh, 1997; Kasper et al., 2001; Mitchell et al., 2017). This has been attributed to increased porosity, increased soil organic matter, root number, and the abundance and diversity of earthworms (Villamil et al., 2006). In this experiment, treatment and date both affected sorptivity (Table 3). No treatment \times date interaction was observed, so sorptivity was pooled over all three dates for analysis. The sorptivity of the ‘Roll down’ treatment was almost double that of the ‘No cover’ treatment (Table 3). In other words, water took nearly twice as long to run off in the ‘Roll down’ system than in the ‘No cover’ treatment.

These results are supported by previous research. Findeling et al. (2003) found that even a minimum amount of mulch ($\sim 1360 \text{ kg ha}^{-1}$) increased sorptivity by $>50\%$. They attributed this increase to the mulch intercepting and storing rain, pathway tortuosity and friction slowing runoff flow, and soil organic matter and microfauna activity stabilizing the soil structure. The higher sorptivity in the ‘Roll down’ treatment compared to the ‘No cover’ treatment was likely due to the cereal rye mulch on the soil surface, which acted to delay runoff in the same ways described in Findeling et al. (2003). The interception and storage of rain can also preserve the soil surface structure and decrease surface sealing. Increased infiltration in the ‘Roll down’ treatment could also be the result of macropores created by the intact cereal rye roots, which have not been destroyed by tillage.

Soil Volumetric Water Content. Soil volumetric water content (VWC) measurements showed that the ‘Roll down’ treatment had consistently higher soil VWC in the top 6.5 cm of soil. Soil VWC values were higher ($P < 0.05$) in the ‘Roll down’ treatment than

any of the other treatments on 4 of the 8 dates measured in 2015, and 9 of the 21 dates measured in 2016 (Figure 3). This higher VWC can be explained by the cereal rye mulch, which slows evaporation from the soil surface, and allows for enhanced water infiltration, as seen above. It is notable that even at the time of planting in 2016 soil VWC was higher in the ‘Roll down’ treatment than in the other treatments. This is

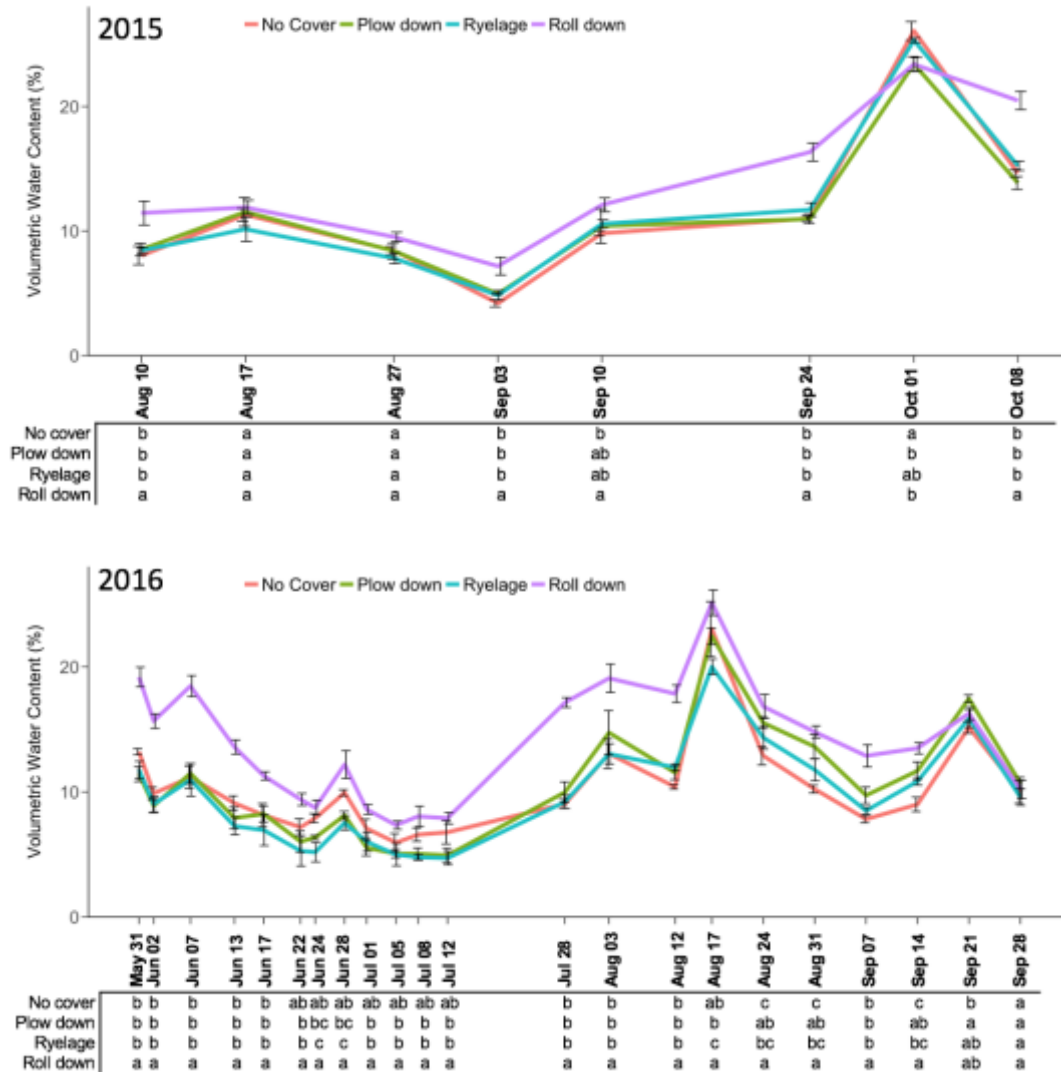


Figure 3. Soil moisture by treatment in 2015 and 2016. Similar letters indicate no significant difference ($P > 0.05$).

contrary to other studies where treatments with cereal rye seeded into a tilled seedbed, as was done here, either had equal or lower moisture content in early spring compared to tilled treatments (Wagner-Riddle et al., 1994; Bernstein et al., 2011).

The higher moisture content of the rolled treatment later in the season is supported in previous research. Bernstein et al. (2011) found that although rolled cereal rye resulted in drier conditions in the early spring, this effect was only seen at depths below 20 cm, and the water deficit at those depths was replenished in just two weeks, surpassing the moisture content in the tilled treatment by late July. In the top 6 cm of soil, soil water content was not lower in early spring, and in July and August, when soybeans need water most, moisture was higher in the cereal rye treatment. Similarly, Wells et al. (2014) found that at three site-years, soil moisture was not different in the rolled cereal rye treatment versus a no cover treatment at the time of rolling and “early” soybean planting, but the rolled cereal rye treatment had higher moisture content three weeks later, at the time of “late” soybean planting.

Soil Temperature. Neither soil weekly average, minimum, nor maximum temperatures were affected by treatment in 2015, and there was no treatment \times date interaction. In 2016, however, weekly average, minimum, and maximum temperatures were all affected by a treatment \times date interaction, so temperature differences between treatments were analyzed for each date (Figure 4 a, b, and c). Both the average weekly temperatures and maximum weekly temperatures in 2016 were lower ($P < 0.05$) in the ‘Roll down’ treatment compared to the other treatments throughout much of the season. Weekly average temperatures in the ‘Roll down’ treatment were lower than all the other treatments by an average of 2.6°C for every week from May 20 to August 5. Weekly maximum temperatures were lower than the other treatments by an average of 6.5°C for ten out of the 14 weeks from May 6 to August 5. After August 5, treatment

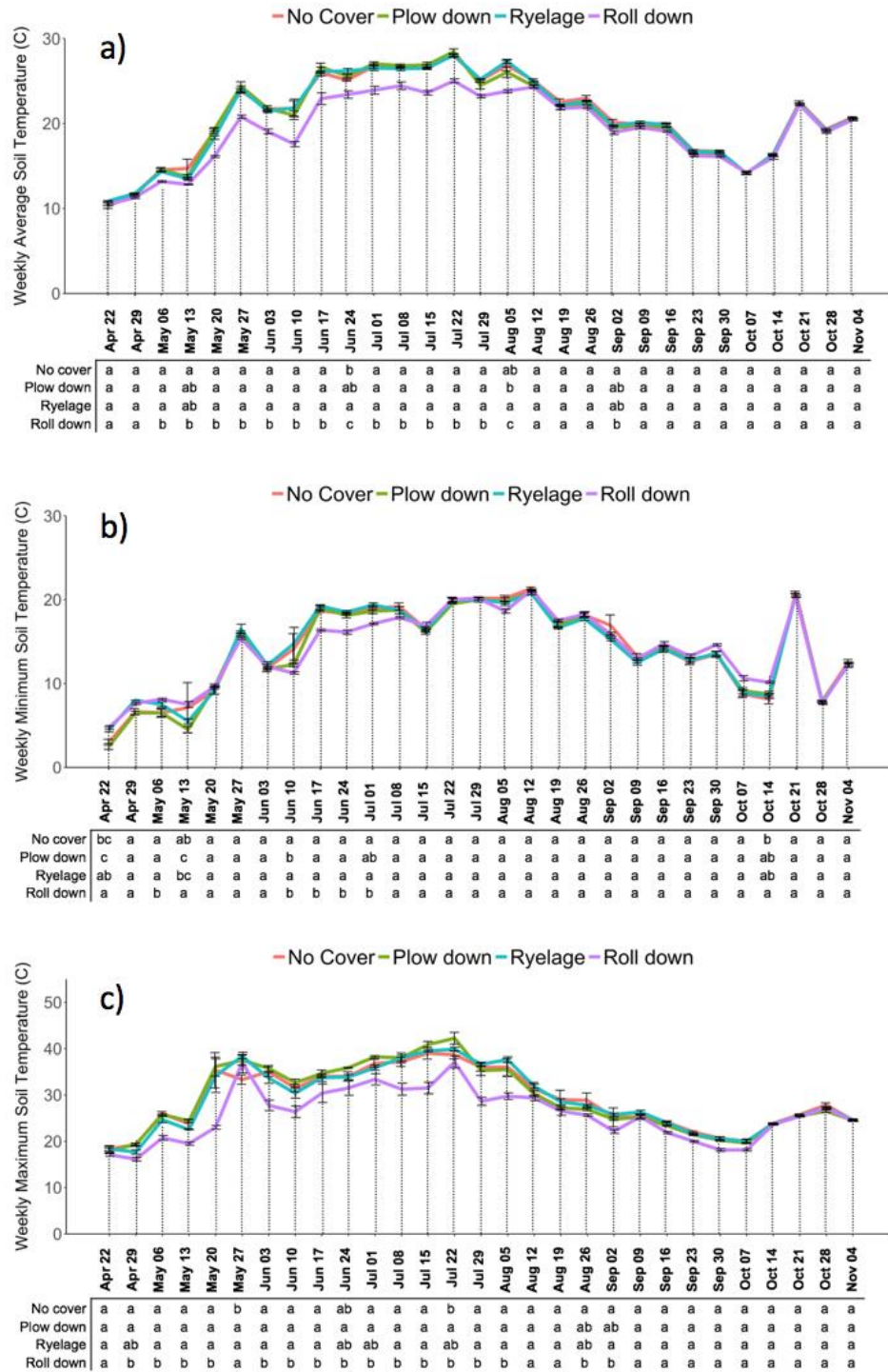


Figure 4. Soil temperatures in 2016, summarized by weekly a) average, b) minimum, and c) maximum weekly temperature. Similar letters indicate no significant difference within each date ($P > 0.05$).

differences largely fade away. This is most likely the reason for no treatment effect found in 2015, as soil temperature in that year was only recorded starting on August 5. In accordance with our findings, Teasdale and Mohler (1993) observed that in past studies, organic mulch usually reduces maximum soil temperature but has little effect on minimum temperature. Studies looking specifically at cereal rye have also revealed lower soil temperatures under mulch (Mochizuki et al., 2008; Jokela and Nair, 2016), although these studies were in vegetable systems. These lower temperatures are caused by insulative effects and the high albedo of residue (Jokela and Nair, 2016). Lower temperatures in the early part of the season in the second year of this experiment may have contributed to delayed soybean germination and growth, but lower temperatures later in the season may have contributed to faster soybean growth due to reduced heat stress. However, we did not test for this, so we cannot say for sure whether or not soil temperature had an effect on soybean growth.

Agronomic Indicators

Cereal Rye Biomass. Cereal rye biomass was affected by treatment and. There was no treatment \times year interaction, so analysis was pooled over years (Table 3). It is important to remember that while the ‘Plow down’ and ‘Roll down’ treatments were cut at the surface, the ‘Ryelage’ treatment was cut at 10 cm above the surface. The ‘Roll down’ treatment had higher cereal rye biomass compared to the other two treatments due to the longer duration of growth. The mean across treatments in 2016 (3434 kg ha⁻¹) was higher than in 2015 (2250 kg ha⁻¹).

The lower cereal rye biomass accumulation in 2015 was most likely due to the later planting date (October 7, compared to September 18 in 2016). It has been widely reported that cereal rye biomass accumulation can be maximized by early sowing (Mischler et al., 2010; Nord et al., 2012; Mirsky et al., 2011). Mirsky (2008) found

that cereal rye planted on August 25 accumulated 65% more biomass compared to cereal rye planted on October 15. Although biomass accumulation was lower in 2015, accumulation for both years was in range of what has been reported in recent years at the same research station in New York: Liebert et al. (2017) reported a mean cereal rye biomass of 5200 kg ha⁻¹ in 2013, and 4500 kg ha⁻¹ in 2014.

The values of cereal rye biomass accumulation seen here are substantially lower than the 8000-kg ha⁻¹ that has been recommended for optimal weed suppression (Mirsky et al., 2012). Mirsky et al. (2012) reported that cereal rye biomass in the mid-Atlantic region typically does not exceed 6000 kg ha⁻¹ unless seeding rate, seeding date, and soil fertility are optimized, in which case biomass levels can reach 12,000 kg ha⁻¹. These numbers are in line with what has been reported in Pennsylvania, where Mirsky et al. (2013) reported cereal rye biomasses ranging from 5974 to 10608 kg ha⁻¹ and Mischler et al. (2010) reported biomass ranging from 5594 to 8940 kg ha⁻¹ for similar seeding and termination dates. However, southeast and central Pennsylvania have a longer growing season than central New York, and this could account for the lower values seen in experiments carried out here.

Weed Biomass. Weed biomass differed by treatment, but not by year, and there was no treatment × year interaction, so analysis was pooled over years (Table 3). Weed biomass in the ‘Roll down’ treatment was almost eight times higher than the mean of the other treatments (Table 3). Although there was not an overall difference between years across treatments, the total weed biomass average in the ‘Roll down’ treatment in 2016 was 304 kg ha⁻¹, only 58% of the 2015 average, which was 522 kg ha⁻¹. The lower weed biomass in 2016 was likely due to dry conditions.

In 2015, 77% of the weed biomass in the ‘Roll down’ treatment was comprised of common ragweed, whereas this species only accounted for 9% of the total weed

biomass in the ‘Roll down’ treatment in 2016. The common ragweed biomass in 2015 was similar to what has been found in previous studies of weed biomass in organic soybean planted into rolled cereal rye. In Liebert et al. (2017), common ragweed comprised 65% and 84% of total weed biomass in two site-years. In Nord et al. (2012), common ragweed comprised 84% of total weed biomass.

Weed biomass in our tilled treatments was low compared with the results of other studies. For example, Mirsky et al. (2013) reported weed biomasses of 674 – 1545 kg ha⁻¹ in five of seven site-years of treatments with incorporate cereal rye. In addition, Bernstein et al. (2014) reported weed biomass of 164 and 410 kg ha⁻¹ in two site years of treatments with incorporated cereal rye. Although weed biomass in the ‘Roll down’ treatment was greater than in the other treatments, it is on the low end for organic rotational no-till systems. Nord et al. (2012) reported that even with early cereal rye seeding, late termination, and high-residue cultivation, weed biomass levels were slightly greater than 1000 kg ha⁻¹. Similarly, Mirsky et al. (2013) reported weed biomass levels of 1601 to 2887 kg ha⁻¹ in rolled, uncultivated fields in five out of seven site-years. Although the weed biomass in the ‘Roll down’ treatment was considerably lower than in these studies, lower values have been reported. Bernstein et al. (2014) reported weed biomass values of 3 and 52 kg ha⁻¹ (in 2008 and 2009, respectively) in a treatment where cereal rye was rolled early, and 5 and 229 kg ha⁻¹ in a treatment where cereal rye was rolled late.

Soybean Density. Soybean density in September was affected by a treatment × year interaction, so treatment means were analyzed separately for each year. Higher overall density in 2016 was due to the higher planting rate reported in the methods section. Though soybean density was not different between treatment means in 2015, density in the ‘Ryelage’ and especially the ‘Roll down’ treatments were lower in 2016

compared to the ‘Plow down’ and ‘No cover’ treatments (Table 3). The extremely low density in the ‘Roll down’ treatment in 2016 was most likely due to poor seed to soil contact, and lack of rain after planting. Some “hair-pinning” was observed at soybean planting (i.e. the rolled cereal rye stems were pushed into the row preventing good soybean seed placement and soil contact). Normally, rain after planting will allow such soybean seeds to imbibe despite poor soil contact, but as there was no substantial rain for over a month after planting in 2016, even seeds with good soil contact might have struggled to germinate. As a result, soybean seedling growth was delayed (Appendix B).

Hair-pinning has been reported in other studies. Mirsky et al. (2013) reported avoidance of hair-pinning when using a lightly fluted coulter, while Clark et al. (2017) had more success removing the coulters entirely, which allowed more weight to be placed on the double disk row openers. Both Clark (2017) and Mirsky et al. (2013) observed that a spiked or spaded (Mirsky et al., 2013) closing wheel was more effective than a solid closing wheel at closing the seed slit. In the experiment reported on here, two rubber press wheels were used in 2015, and one rubber press wheel was used with a curvetine (Dawn Manufacturing, Sycamore, IL) in 2016. In this experiment, it is likely that the lower density was due to the combination of less than ideal seed placement and lack of rain.

Soybean Yield. Soybean yield was affected by treatment and year. The average soybean yield across treatments in 2015 (2861 kg ha^{-1}) was 45% higher ($P < 0.05$) than the average soybean yield in 2016 (1937 kg ha^{-1}). To analyze treatment means, separate models were used for each year, as the variance was not equal between years (Table 3). Higher variance in 2016 was most likely the result of hand-harvesting and the grains, as opposed to using a combine to harvest, as was done in 2015. Treatment

affected soybean yield in both years. In 2015, the ‘Roll down’ treatment had lower yield than the ‘Plow down’ treatment, but the ‘Ryelage’ yield did not differ from any other treatment. In 2016, the ‘Roll down’ treatment had lower yield than the ‘No cover’ treatment, and the ‘Ryelage’ and ‘Plow down’ treatments did not differ from any other treatment (Table 3).

A reduction in soybean yield in rolled cereal rye has been observed elsewhere, but not as severe as what occurred in this experiment in 2016, which amounted to a 43% loss in the ‘Roll down’ treatment compared to the ‘No cover’ treatment. Davis (2010) reported a loss of at least 29% with rolled cereal rye (6,000 – 7,100 kg ha⁻¹ of cereal rye biomass), but in other experiments, no reduction in yield was reported in rolled cereal rye systems (Smith et al., 2011). The reduction in yield in the ‘Roll down’ treatment in 2016 was most likely due to poor establishment, caused by a combination of poor seed to soil contact and the lack of rain after planting, as discussed previously, and to slower growth throughout most of the season (Appendix B). The slowed soybean growth was most likely due to the drought. Although the volumetric soil water content was higher in the top 6.5 cm of soil, the soil below that could have been drier than other treatments, due to the longer duration of cereal rye growth in the spring. The observation that irrigation improved soybean growth in the ‘Roll down’ treatment but not in the other treatments supports the conjecture that the soybeans in the ‘Roll down’ treatment were suffering from lack of moisture. The increase in growth stage immediately after irrigation in the ‘Roll down’ treatment, not seen clearly in the other treatments (Appendix B), also supports this explanation.

Economic Analysis

Variable Costs. The ‘Ryelage’ treatment was by far the most costly, mainly due to the expense of baling (Table 4). The ‘No cover’ treatment was the least expensive, due to

the absence of costs associated with seeding the cereal rye. The ‘Roll down’ treatment was the second-least expensive (7 and 17% higher costs compared to ‘No cover’ in 2015 and 2016, respectively), due to the absence of cultivation, except for high-residue cultivation in 2015. The ‘Plow down’ treatment was second-most expensive (27 and 23% higher costs compared to ‘Roll down’ in 2015 and 2016, respectively), since it included both the costs associated with the cereal rye and cultivation. Although the ‘Roll down’ treatment did have higher costs than the ‘No cover’ treatment, it is interesting to note that the costs of these treatments are very close, especially in 2015, when there was considerably more tillage than in 2016. This suggests that, in a rolled cereal rye system, the reduction of costs from not cultivating has the potential to compensate for the additional cost of seeding cereal rye.

The higher cost of the ‘Roll down’ treatment compared to the ‘No cover’ treatment is similar to what was found by Delate et al. (2012), in which a system with a rolled hairy vetch and cereal rye mixture had 13% higher total costs (fixed and variable) compared to a system that was tilled with no cover crop. Our finding that the ‘Plow down’ treatment was more costly than the ‘Roll down’ treatment is supported by Bernstein et al. (2011), in which the a system with tilled cereal rye had 9% greater variable costs compared to a rolled system.

Labor Required. The amount of labor required for each treatment largely follows the pattern of the treatment costs (Table 4). However, there is one exception: the labor required for the ‘Roll down’ treatment is less than the labor required for the ‘No cover’ treatment. This is because cultivation is much more time-consuming than seeding cereal rye. It is important to note that the ‘Roll down’ treatment has a considerably lower labor requirement than all other treatments. Taking an average between the two years, labor required in the ‘Roll down’ treatment represented an 11% reduction

Table 4. Variable costs and labor hours associated with operations and materials by treatment. The occurrence of an operation in a treatment is marked with an “x”.

2015							
Operation	Season	Operation and Material† Costs (USD ha ⁻¹)	Labor (hour ha ⁻¹)	Operation Occurrence by Treatment			
				No cover	Plow down	Ryelage	Roll down
Moldboard plow	Fall	\$51.38	0.59		x	x	x
Disk + harrow	Fall	\$46.68	0.20		x	x	x
Drill rye	Fall	\$189.45	0.36		x	x	x
Mow	Spring	\$38.78	0.28			x	
Rake	Spring	\$23.34	0.71			x	
Bale‡	Spring	\$335.59	0.90			x	
Roll/crimp rye	Spring	\$9.88	0				x
Moldboard plow	Spring	\$51.38	0.59	x	x	x	
Disk + harrow	Spring	\$46.68	0.20	x	x	x	
Plant soybeans (conventional)	Spring	\$236.58	0.18	x	x	x	
Plant soybeans (no-till)	Spring	\$238.06	0.19				x
High residue cultivation§	Summer	\$31.27	0.19				x
Interrow cultivation (x 5)§	Summer	\$37.79 (x 5)	0.19 (x 5)	x	x	x	
Combine soybeans	Fall	\$83.24	0.36	x	x	x	x
Total Costs				\$606.83	\$894.34	\$1,292.05	\$649.96
Total Labor				2.29	3.44	5.33	1.91
2016							
Operation	Season	Operation and Material† Costs (USD ha ⁻¹)	Labor (hour ha ⁻¹)	Operation Occurrence by Treatment			
				No cover	Plow down	Ryelage	Roll down
Moldboard plow	Fall	\$51.38	0.59		x	x	x
Disk + cultmulch	Fall	\$46.68	0.20		x	x	x
Drill rye	Fall	\$189.45	0.36		x	x	x
Mow	Spring	\$38.78	0.28			x	
Rake	Spring	\$23.34	0.71			x	
Bale‡	Spring	\$471.33	0.90			x	
Roll/crimp rye	Spring	\$9.88	0				x
Moldboard plow	Spring	\$51.38	0.59	x	x	x	
Disk + harrow	Spring	\$46.68	0.20	x	x	x	
Plant soybeans (conventional)	Spring	\$236.58	0.18	x	x	x	
Plant soybeans (no-till)	Spring	\$238.06	0.19				x
Tine-weeding§	Spring	\$21.41	0.10	x	x	x	
Interrow cultivation (x 2)§	Summer	\$37.79 (x 2)	0.19 (x 2)	x	x	x	
Combine soybeans	Fall	\$83.24	0.36	x	x	x	x
Total Costs				\$514.87	\$802.38	\$1,335.83	\$618.69
Total Labor				1.81	2.97	5.13	1.72

†Costs for drilling cereal rye and planting soybeans include seed costs (\$144.50/ha for rye and \$187.18/ha for soybeans).

‡Cost of baling is calculated by weight of biomass, so this value depends on the ryelage yield. The value presented here is the average cost of baling for each year. This also affects the total cost of the 'Ryelage' treatment.

§Operations differed between years.

compared to the ‘No cover’ treatment, a 43% reduction compared to the ‘Plow down’ treatment, and 65% reduction compared to the ‘Ryelage’ treatment. Especially compared to the ‘Plow down’ and ‘Ryelage’ treatments, this is a drastic decrease in labor, and could allow the farmer to engage in other income-generating activities, thereby making up for any lost income in a dry year. The lower labor requirements of the rolled system compared to tilled cover crop systems has been documented in previous research (Bernstein et al., 2011; Ryan, 2010).

Return Over Variable Costs. Separate models were used to analyze return over variable costs, as the variance was much higher in 2016 (Table 3), due to the high variation in soybean yield that year, described above. The ‘Ryelage’ treatment was the most profitable treatment in 2015, and more profitable than the ‘Plow down’ and ‘Roll down’ treatments in 2016. This is mostly explained by the extra profit gained by the sale of the ryelage, as the soybean yields were not different in the ‘Ryelage’ treatment compared to any other treatment in either year.

The ‘Roll down’ treatment performed well in 2015, with return over variable costs comparable to both the ‘Plow down’ and ‘No cover’ treatments. The lack of difference in profitability between the ‘Roll down’ and ‘Plow down’ treatments ($P > 0.05$) is surprising given the higher yield in the ‘Plow down’ in 2015. This could be due to the added expense in the ‘Plow down’ treatment of drilling cereal rye, which was not countered by a reduction in fuel and labor cost, as it was in the ‘Roll down’ treatment. In 2016, the low yield of the ‘Roll down’ treatment resulted in similarly low return over variable costs, only 35% and 27% of the returns in the ‘No cover’ and ‘Ryelage’ treatments, respectively ($P < 0.05$). The lower profit in the ‘Roll down’ treatment compared to the ‘No cover’ treatment was clearly because of the lower yield

($P < 0.05$), while the lower profit in the ‘Roll down’ compared to the ‘Ryelage’ treatment was due to the lack of extra income from ryelage.

The lack of difference in returns between the ‘Plow down’ and ‘Roll down’ treatments in either year is contrary to the findings in Bernstein et al. (2011), where a tilled system with cereal rye was 36% more profitable than a no-till system with rolled or mowed cereal rye. In 2015, this discrepancy can be explained by the fact that the mean yield in the ‘Roll down’ treatment was only 14% below the yield in the ‘Plow down’ treatment, compared to a 32% reduction in yield in the no-till system in Bernstein et al. (2011). However, in 2016, this discrepancy is most likely due to the high standard error in our model ($\pm 208 \text{ USD ha}^{-1}$), as the mean return for the ‘Plow down’ treatment was indeed 42% higher than the mean for the ‘Roll down’ treatment.

The higher return in the ‘No cover’ treatment compared to the ‘Roll down’ treatment in 2016 is similar to findings in Delate et al. (2012), in which a treatment that was tilled with no cover crop had higher returns than a treatment with rolled cereal rye and hairy vetch (Delate et al., 2012). This is contrary to the equal returns between those treatments in 2016, likely because the yield of the rolled system in our experiment was more comparable to the tilled, no cover system than in Delate et al. (2012).

CONCLUSIONS

We tested the effects of different cereal rye management practices before soybean in organic production on several cropping system performance indicators. The ‘Roll down’ treatment had some soil health benefits over the ‘No cover’ treatment, e.g., increasing sorptivity and soil respiration. We also noticed a trend

toward higher soil respiration, POXC, sorptivity, and aggregate stability when cereal rye was rolled, compared to when no cereal rye was seeded. Weed biomass was greater in the 'Roll down' treatment in both years compared to all other treatments, but levels were still relatively low for organic production. In 2015, although soybean yield was higher in the 'Plow down' treatment compared to the 'Roll down' treatment, the yield in the 'Roll down' treatment was not different from either the 'No cover' or the 'Ryelage' treatment, and all treatments produced relatively high soybean yields. In 2016, however, soybean yield in the 'Roll down' treatment suffered considerably, mainly due to the lack of rain at the beginning and throughout most of the growing season.

The lower soybean yield in the 'Roll down' treatment in 2016 suggests that growers should be aware of challenges with dry conditions over the winter and in early spring if implementing a rolled system. This conclusion is supported in Clark et al. (2017), where severe drought in 2012 led to a 28% reduction in soybean yield in an organic no-till system with rolled cereal rye compared to a tilled system with no cereal rye – a difference that was not seen in 2013, when there was sufficient moisture. It is promising, however, that in 2015, when rain was adequate, soybean yield in the rolled system was comparable to the tilled systems with and without cereal rye, as was observed in Smith et al. (2011), Mischler et al. (2010). These observations suggest that irrigation in early spring, especially at time of planting, has the potential to eliminate establishment problems related to lack of spring rain in a rolled system.

In contrast to the 'Roll down' treatment, the 'Ryelage' treatment showed no increase in weed biomass or decrease in crop yield when compared to the other treatments. In addition, the ryelage gives considerable added profit to the grower. Although the 'Ryelage' treatment did not show any differences in soil health in this experiment, there was a noticeable trend toward higher soil respiration, POXC, and

sorptivity compared to the ‘No cover’ treatment. Future research should further explore the potential for ryelage to improve soil health. The profitability of growing and harvesting cereal rye prior to soybean shows great potential for increasing the adoption of cover crops, and if future research confirms the trend towards enhanced soil health noticed here, the adoption of this method could improve the sustainability of soybean cropping systems.

Overall, our results support our hypothesis that compared to the no cover control, incorporating cereal rye into a rotation prior to soybean can improve soil health, maintain weed suppression and soybean yield, and improve profitability, but that these benefits vary depending on management method. No one method provided all of these benefits. The ‘Roll down’ treatment improved soil health and reduced labor, but weeds were more abundant and soybean yields and profitability were lower in the second year. The ‘Ryelage’ treatment maintained weed suppression and soybean yield and increased profitability, but did not significantly improve soil health and required substantially more labor. Growers will have to consider these pros and cons when choosing between these management methods.

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APPENDIX A

Table A1. Baseline soil test results from samples collected in May of 2015 and 2016.

Testing by University of Maine Soil Testing Service.

Year	pH	P	K	Mg	Ca	Al	Fe	Mn	Zn	Organic Matter (%)
----- (kg ha ⁻¹) -----										
2015	7.5	4.4	75	587	5358	11	1.8	22	0.9	2.8%
2016	7.4	6	95	717	4866	11	1.9	52	0.8	2.7%

Soil samples for base nutrient analysis were taken on May 5, 2015 and May 4, 2016 before treatments were applied. Soil was sampled with 2.5 cm-diameter probe to a depth of 20 cm. Thirty cores were taken per block in 2015, and 12 per block in 2016¹. There were no major differences between sites. For both sites, the pH was common for the soil series (Lima and Honeoye), as the parent material is very calcareous. Phosphorus was low for general crop production, and potassium was average. Magnesium and calcium were very high, but can be explained by the parent material. Iron and Manganese were deficient to marginal for crop growth. Aluminum levels were low, reflecting the high pH. The percent organic matter was lower than what one would see on local farms with a long-term history of organic management, but to be expected for the research farm.

¹ Higher number of cores in 2015 was because soil was initially going to be used for weed bioassays in addition to base nutrient analysis.

APPENDIX B

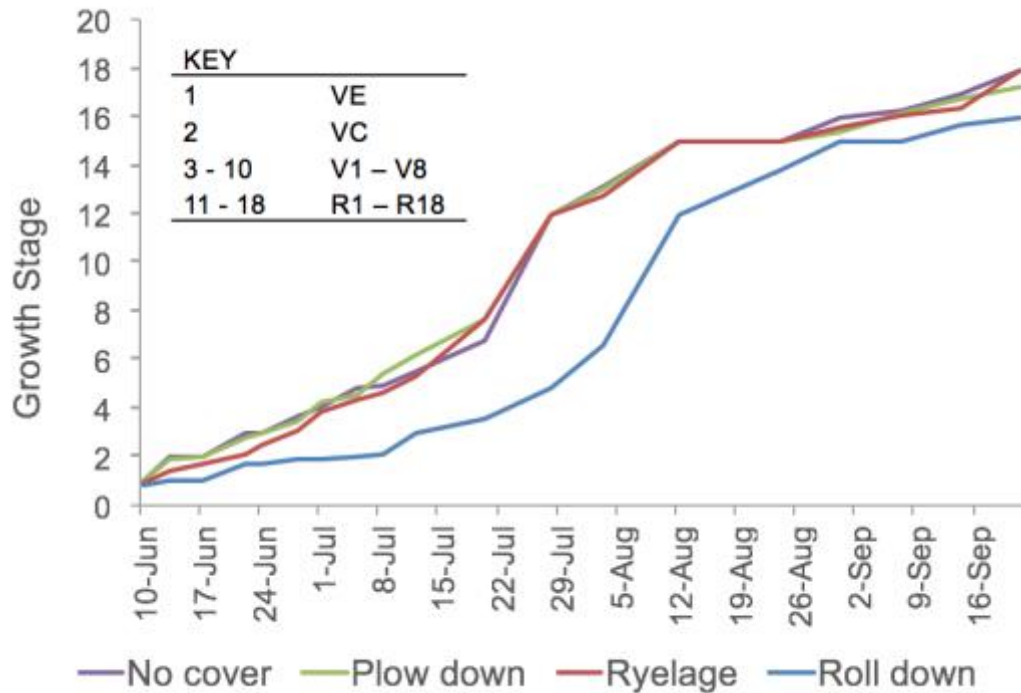


Figure B1. Soybean growth stages by treatment over time, 2016.

Soybean growth stages were recorded at four locations within each plot in 2016, biweekly from May 31 to July 12, and weekly until September 28. Soybean development lagged in the ‘Roll down’ treatment in the first half of the season, but began to accelerate in late July when precipitation started to accumulate (see Figure 1). A small surge in development can be observed in the ‘Roll down’ treatment after irrigation occurred on July 7-8, which is not present in the other treatments. Our observations verify this surge in development, as soybeans in the ‘Roll down’ treatment in the area that received irrigation were no longer showing signs of water stress, but soybeans outside the area in that treatment still had flipped and clamped leaves.